RT-Xen: Real-Time Virtualization in Xen

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Agenda

Main Sections

- **P**roblem **S**tatement
- **B**ackground
- **R**T-Xen
- **D**emonstration
- **A**ctive **R**esearch **T**opics
- **C**onclusion

Agenda

Main Sections

- **Problem Statement**
  - Contemporary Utility of System Virtual Machines
  - Need for Real-Time Performance
- Background
- RT-Xen
- Demonstration
- Active Research Topics
- Conclusion

Problem Statement

Contemporary Utility of System Virtual Machines

- Purpose of System Virtual Machines
  - Support multiple environments (users) on a single machine

Utility

- Hardware is becoming increasingly **more capable**
  - **Example:** Intel Xeon E7-8894 (**48 Cores, 60 MB L3 Cache**, Up-to **3-TB Main Memory**)
- Single user not enough to employ all resources
- **Solution:** Virtualization!
- **Use-Case:** Amazon Cloud
  - Multiple users utilizing high-end physical (server) machines in virtualized environments

Problem Statement

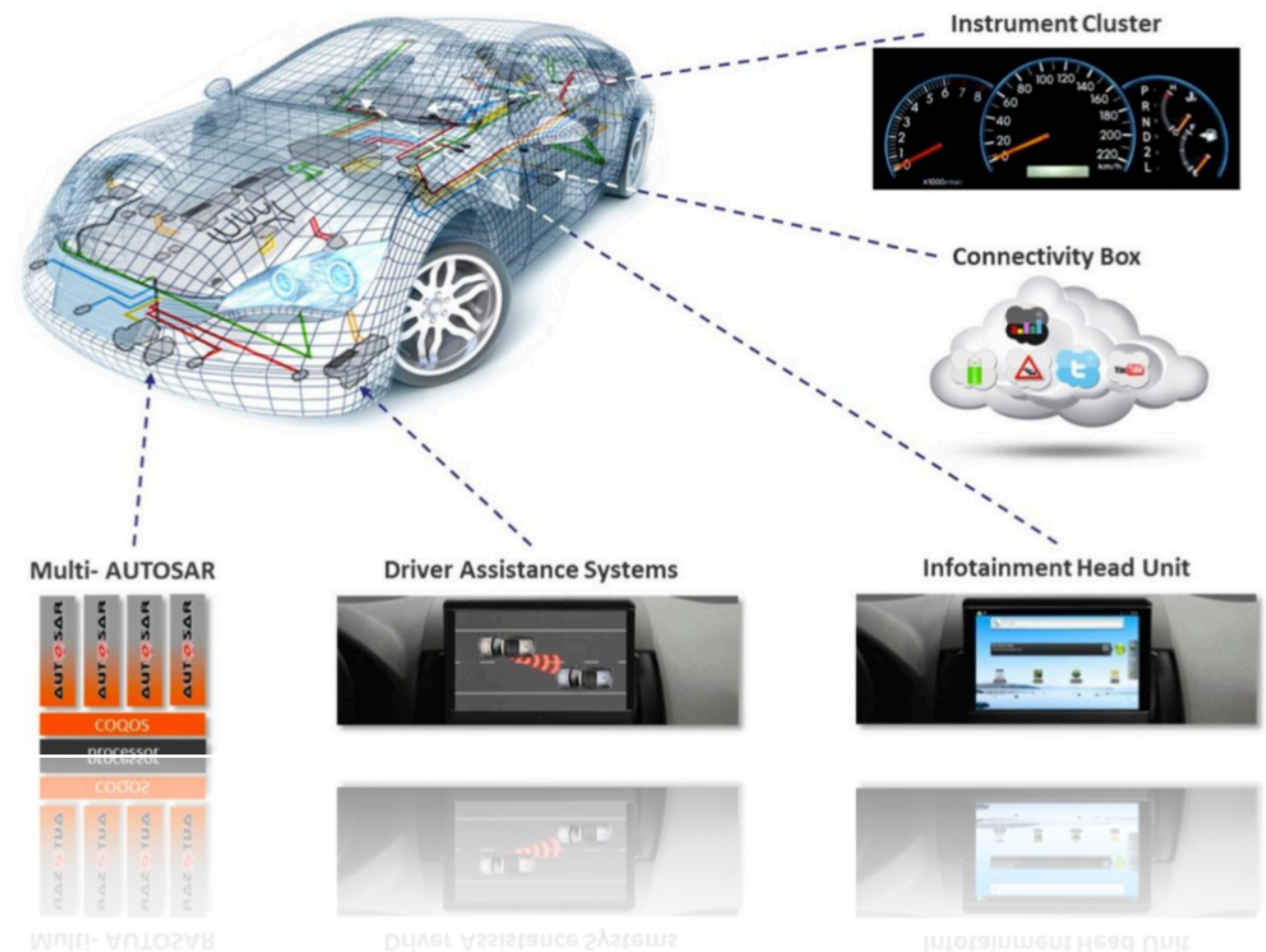
Contemporary Utility of System Virtual Machines

- Similar advancements in COTS embedded platforms
  - **SWaP** (**S**ize, **W**eight and **P**ower) requirements are leading to **more consolidation**
  - **Example:** NVIDIA Jetson Xavier (**8-Cores**, **4-MB LLC**, **512-Core** Volta **GPU**, **2 DL-Accelerators**, VLIW **Vision Processor**, **16-GB Main Memory**)
- **Use-Case:** Virtualization for Cars
  - 100s of ECUs → N-physical processors
  - Integrate multiple systems on a common platform (e.g., Xavier)

Problem Statement

The Need for <u>Real-Time</u> Performance

- Different systems have different QoS requirements
  - Infotainment System - Best-Effort Requirement
  - Driver Assistance System - Soft Real-Time Requirement
  - Emergency Braking System - Hard Real-Time Requirement



Reference: https://www.edn.com/design/automotive/4399434/Multicore-and-virtualization-in-automotive-environments

Problem Statement

The Need for Real-Time Performance

"In the virtualized environment, the **real-time requirements** of the *individual systems being virtualized* must be respected."

- **Example**
  - VM-1: Braking system requires **5-ms response latency**
  - VM-2: Lane keeping assist requires **bounded tardiness** (*the extent to which a job can miss its deadline*)
  - VM-3: Streaming application requires a 20-FPS **throughput**
- Xen, by default, cannot guarantee this under the credit based scheduling paradigm
  - Each VM will get 1/3 of the CPU credit (**P**roportional **F**airness)
  - Hard real-time tasks cannot be ***analytically*** guaranteed their deadlines

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- Problem Statement
- **Background**
    - Meaning of Real-Time
    - Concepts from Scheduling Theory
        - Fair Scheduling
        - Real-Time Scheduling
- RT-Xen
- Demonstration
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Background

Meaning of <u>Real-Time</u>

- Traditional meaning of **Correctness**
  - Given an input, the system computes the ***logically right response***
    - **Example:** 2+2=4
- <u>**Real-Time**</u> **Correctness**
  - Given an input, the system computes the ***logically right response within a <u>deterministic</u> amount of time***
  - **Example:** An autonomous car applies brakes <u>**within 30-usec**</u> of detecting an object in its way
  - A logically correct output at a wrong time is a **fault!**

Background

Concepts from Scheduling Theory

- **Purpose of Scheduling:** Sharing of a resource among multiple clients
  - **Example:** CPU scheduling shares the CPU (**resource**) among multiple processes (**clients**)
- Different scheduling schemes can provide different guarantees
  - **Fairness:** Given N clients, each receives <u>**1/Nth portion of the resource**</u>
  - **Real-Time Response:** Given N clients, the response time constraints of each can be satisfied based on <u>**their priority**</u>

Background

Fair Scheduling

- **Purpose:** Ensure proportional fairness among clients
- **Example: CFS** (**C**ompletely **F**air **S**cheduler) in Linux, **Credit** Scheduler in Xen
- **Fair Scheduling Illustration**
    - Two VCPUs on a single-core system
    - Scheduling Granularity: 6-msec
    - At each 6-msec boundary, both VCPUs would have been given **equal amount of CPU time**

Background

Real-Time Scheduling

- **Purpose:** Each client can execute its job with **deterministic** latency
- **Example: FIFO, Round-Robin, Deadline** in Linux
- **RT Scheduling (FIFO) Illustration**
  - Two VCPUs on a single-core system, VCPU-1 high priority, VCPU-2 low priority
  - VCPU-1 guaranteed execution on physical core whenever ready
  - Classic response time analysis (RTA) can be applied to **analytically verify** schedulability

Background

Real-Time Scheduling in Xen

"In a virtualized environment, real-time schedulability of the system cannot be guaranteed unless the scheduler in each layer of abstraction is using a real-time policy."

- Xen, with credit scheduler, can provide **no guarantee** on the ***latency*** of the jobs running in each VM

- **Illustration**

  - System virtualized by Xen (Credit Scheduler)

  - VM-1 running a real-time OS with FIFO policy

  - VM-2 running Linux with CFS policy

  - Tasksets in VM-1 cannot be guaranteed real-time performance since the root scheduler is not real-time

Agenda

Main Sections

RT-Xen

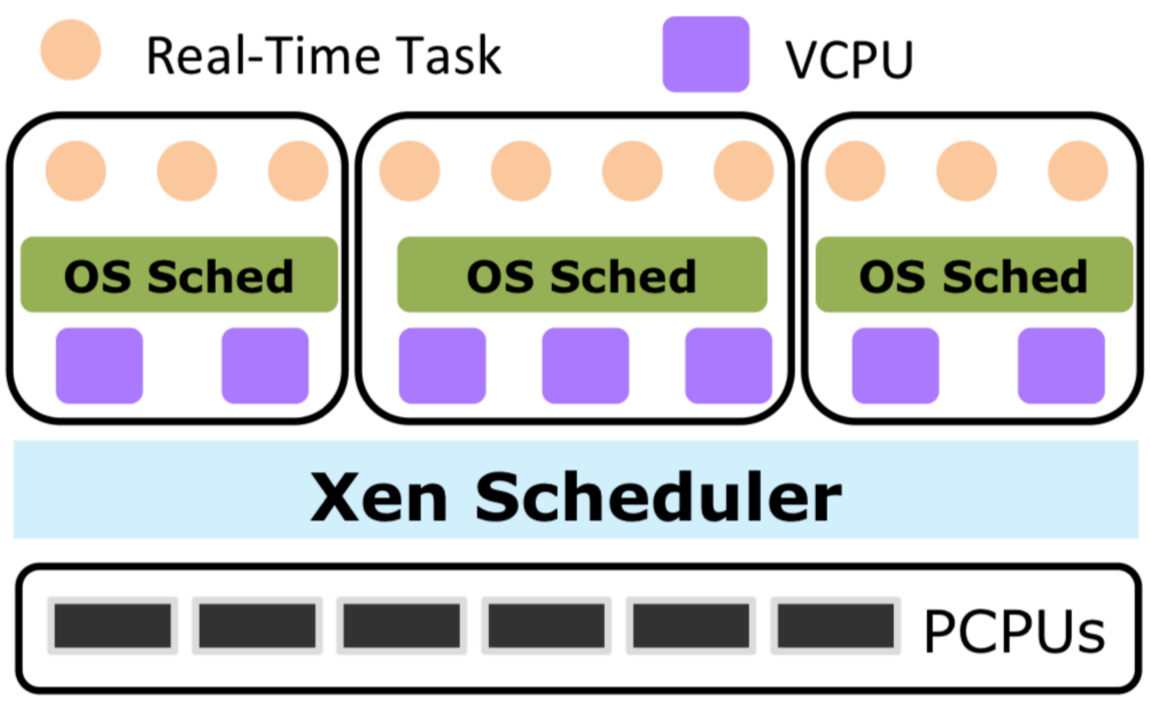
Features

- Real-Time VMM based on Xen
  - Real-Time **CPU** Sharing among VMs
  - Real-Time arbitration of **IO** / **N**etwork resources
  - **Spatial Isolation** among VMs at Hardware Level
    - Cache Level Isolation
    - Memory Level Isolation
- Built on **C**ompositional **S**cheduling **P**aradigm
  - Provides real-time guarantees to tasks inside individual VMs
- Open-Source

RT-Xen

Bringing RT to Xen

- **Xen:** Baremetal (i.e., Classic) System Virtual Machine
    - Runs **paravirtualized** or **fully virtualized** OSes
- **VMM Scheduler:** Credit based
    - Assign Round-Robin quanta of execution on physical CPUs to each client (i.e., VCPU) to ensure proportional fairness



Reference: https://www.cse.wustl.edu/~lu/papers/emsoft14-rt-xen.pdf

RT-Xen

Bringing <u>RT</u> to <u>X</u>en

- **RT-Xen**
  - Each virtual machine is considered a **real-time** resource interface defined by parameters
    - <u>**P**</u>eriod, <u>**B**</u>udget, <u>**#**</u> of VCPUs
  - The runtime parameters assigned to each interface are determined based on its requirement using <u>**C**</u>omposition <u>**S**</u>cheduling <u>**T**</u>heory
  - Each VM is scheduled with its assigned parameters using a <u>**r**</u>eal-<u>**t**</u>ime <u>**s**</u>cheduling policy

RT-Xen

Scheduling Policies

- Supports both **Global** and **Partitioned** scheduling
  - Dictates placement of VCPUs
- Allows selection of **Static** and **Dynamic** scheduling schemes
  - Dictates ordering of VCPUs
  - **Static:** RMS (FIFO, RR etc.)
  - **Dynamic:** EDF
- Allows **Server** based scheduling schemes
  - **M**echanism for **R**esource **I**solation
  - **P**eriodic, **P**olling, **D**eferrable, **S**poradic

RT-Xen

Scheduling Policies: Development over the Years

- RT-Xen 1.0
  - Introduced <u>**S**</u>ingle-<u>**C**</u>ore RT scheduling
- RT-Xen 2.0
  - <u>**M**</u>ulti-<u>**C**</u>ore RT scheduling
    - RT-global
    - RT-partition

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- **Demonstration**
    - Xen vs RT-Xen
- Active Research Topics
- Conclusion

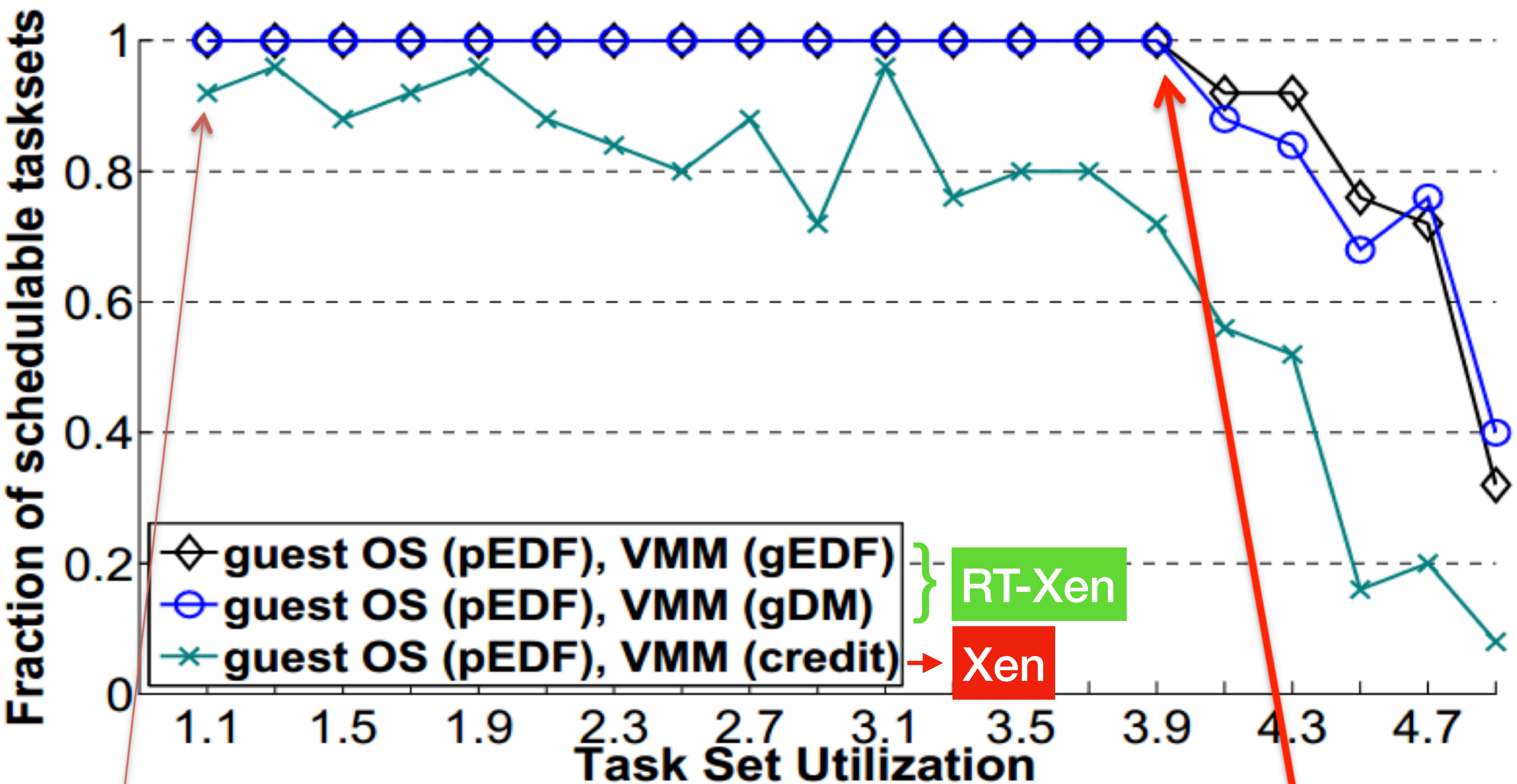
Demonstration

Xen vs RT-Xen

- **Setup**
  - **Platform:** Intel i7 Processor, 6 cores, 3.3 GHz
  - **Software:** Xen-4.3 patched with RT-Xen
  - **Workload:** Periodic real-time tasksets with increasing utilization
  - **Metric:** Proportion of tasksets which are **schedulable**
    - If all tasksets (i.e., 100%) of a given utilization are schedulable, the algorithm is said to satisfy **real-time schedulability requirement**

Demonstration

Xen vs RT-Xen



- Credit misses deadlines at 22% of CPU capacity.

- RT-Xen delivers real-time performance at 78% of CPU capacity.

Reference: https://www.cse.wustl.edu/~lu/papers/emsoft14-rt-xen.pdf

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- **Active Research Topics**
  - Hardware Level Resource Isolation
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Active Research Topics

Hardware Level Resource Isolation

- In Multicore Platforms, resource sharing in hardware can lead to unpredictable behavior
    - **Example**
        - Dual core system with **shared** L̲ast-L̲evel C̲ache (LLC)
        - Miss in LLC incurs **100x** penalty to memory request
        - Application running in VCPU of Core-1 fits in LLC
        - Application running in VCPU of Core-2 thrashes the LLC
        - When run **simultaneously**, the execution time of application on Core-1 will increase 100x
            - Real-Time guarantees cannot be satisfied in an unmanaged system

Active Research Topics

Hardware Level Resource Isolation

"In VMM context, real-time scheduling of CPUs is not enough to provide guaranteed latencies to virtual guests."

- Ensure isolation among VMs at hardware level
  - **Common Solution:** Partitioning
- Paritioning in RT-Xen
  - vCAT: Dynamic Cache Management using CAT Virtualization (2017)
    - Mechanism to parition shared LLC among virtual guests in RT-Xen in Intel Haswell processors
  - Multi-Mode Virtualization for Soft Real-Time Systems (2018)
    - Memory level isolation among VMs using page-coloring

Conclusion

Key Takeaways

- Xen provides a mechanism to effictively utilize immensely capable emerging hardware platforms among multiple users
- RT-Xen ensures real-time schedulability of virtual guests in Xen
  - Implements real-time scheduling policies
  - Ensures hardware level isolation among virtual guests
  - Immensely improves real-time schedulability over the default credit scheduler of Xen

QUESTIONS?